CP violation in b-hadron decays to charmless charged two-body final states at LHCb

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Outline

• Motivations, CPV observables and current experimental status

• Main ingredients of presented analyses:
  – Measurement of CP asymmetries in two-body $B^{0}_{(s)}$-meson decays to charged pions and kaons
    [arXiv:1805.06759 – submitted to PRD]
  – Search for CPV in $\Lambda_{b}^{0}\rightarrow pK^{-}$ and $\Lambda_{b}^{0}\rightarrow p\pi^{-}$ decays
    [LHCb-PAPER-2018-025 – will appear soon on arXiv]

• Conclusions
Motivation

- A rich set of physics processes participates in the $H_b \rightarrow h^+ h'^-$ decays
  - Tree and penguin decay topologies
  - Neutral B mixing

- CPV observables are sensitive to CKM angles $\gamma$ and $\alpha$ and mixing phases $\phi_s$ and $\phi_d$
  - presence of loop diagrams introduces hadronic uncertainties
  - presence of loop diagrams makes the CPV observables sensitive to New Physics contributions

CPV observable

- Time-dependent CPV asymmetries ($B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$)

$$A(t) = \frac{\Gamma_{B^0(s) \to f}(t) - \Gamma_{B^0(s) \to f}(t)}{\Gamma_{B^0(s) \to f}(t) + \Gamma_{B^0(s) \to f}(t)} = -C_f \cos \left( \Delta m_{d(s)} t \right) + S_f \sin \left( \Delta m_{d(s)} t \right) \cosh \left( \frac{\Delta \Gamma_{d(s)}}{2} t \right) + A_f^{\Delta \Gamma} \sinh \left( \frac{\Delta \Gamma_{d(s)}}{2} t \right)$$

- CPV in the decay

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

- CPV from mixing/decay interference

$$S_f = \frac{2 \text{Im} \lambda_f}{|\lambda_f|^2 + 1}$$

Condition not imposed

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta \Gamma}|^2 = 1$$

- Time-integrated CPV asymmetries ($B^0 \to K^+\pi^-$, $B^0_s \to \pi^+K^-$, $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$)

$$A_{CP} = \frac{|\bar{A}_f|^2 - |A_f|^2}{|\bar{A}_f|^2 + |A_f|^2}$$
Current status (TD CPV)

\[ B^0 \rightarrow \pi^+\pi^- \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( S_{CP} (\pi^+\pi^-) )</th>
<th>( C_{CP} (\pi^+\pi^-) )</th>
<th>Correlation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>(-0.68 \pm 0.10 \pm 0.03)</td>
<td>(-0.25 \pm 0.08 \pm 0.02)</td>
<td>(-0.06) (stat)</td>
<td>PRD 87 (2013) 052009</td>
</tr>
<tr>
<td>Belle</td>
<td>(-0.64 \pm 0.08 \pm 0.03)</td>
<td>(-0.33 \pm 0.06 \pm 0.03)</td>
<td>(-0.10) (stat)</td>
<td>PRD 88 (2013) 092003</td>
</tr>
<tr>
<td>LHCb ( \int dt = 1.0 \text{ fb}^{-1} )</td>
<td>(-0.71 \pm 0.13 \pm 0.02)</td>
<td>(-0.38 \pm 0.15 \pm 0.02)</td>
<td>0.38 (stat)</td>
<td>JHEP 1310 (2013) 183</td>
</tr>
<tr>
<td>Average</td>
<td>(-0.66 \pm 0.06)</td>
<td>(-0.31 \pm 0.05)</td>
<td>0.00</td>
<td>HFAG correlated average ( \chi^2 = 0.9/4 \text{ dof (CL}=0.92 \Rightarrow 0.1\sigma) )</td>
</tr>
</tbody>
</table>

- \( C_{\pi\pi} \) and \( S_{\pi\pi} \) are well constrained by B-factories and LHCb
  - All three experiments are in good agreement
- \( C_{KK} \) and \( S_{KK} \) are measured only by LHCb using 1 fb\(^{-1}\) @ 7 TeV
  - No measurement is available for \( A_{\Delta\Gamma}^{KK} \)

JHEP 1310 (2013) 183 – \( B^0 \rightarrow K^+K^- \)

\[ C_{KK} = 0.14 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)}, \]
\[ S_{KK} = 0.30 \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst)}, \]
Current status (TI CPV)

- Direct CPV in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ are dominated by LHCb measurement (with $L = 1 \text{ fb}^{-1}$)
  

- Direct CPV in $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ have been measured only by CDF so far
  
  [Phys. Rev. Lett. 113 242001 (2014)]

\[
A_{\text{CP}}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08 \text{ (stat.)} \pm 0.04 \text{ (syst.)}
\]

\[
A_{\text{CP}}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)}
\]
Main experimental ingredients to measure CPV

• Time-integrated CPV:
  – Final-state detection asymmetries ($A_F$)
  – Production asymmetry ($A_P$)
    • Thanks to a time-dependent analysis of $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ $A_{CP}$ can be measured already free from $A_P$
    • For $\Lambda_b^0$ decays it is determined by difference with respect to other B species [Phys. Lett. B 774 (2017) 139]

\[ A_{\text{exp.}} \approx A_{\text{CP}} + A_F + A_P \]

• Time-dependent CPV:
  – Flavour tagging
  – Decay-time resolution
  – Decay-time acceptance

\[ A_{\text{exp.}}(t) \sim (1-2\omega) \exp(-\sigma_t^2 \Delta m^2/2) A(t) \]

\[ A_{\text{exp.}}(t) \sim (1-2\omega) \exp(-\sigma_t^2 \Delta m^2/2) A(t) \]
Event selection

- Both analyses are based on the full Run1 statistics
  - 1 fb\(^{-1}\) @ 7 TeV + 2 fb\(^{-1}\) @ 8 TeV
- Event selection is based on two main ingredients
  - Particle identification
    - Separate the final states and reduce amount of cross contamination from other \(H_b \to h^+h^-\) modes ⇒ Calibrated using \(D^{*+} \to D^0(K^-\pi^+)\pi^+, \Lambda \to p\pi^-\) and \(\Lambda_c^+ \to pK^-\pi^+
  - MVA algorithm based on BDT to reduce combinatorial background

\(~94k\ B^0 \to K^+\pi^- ; ~7k\ B^0_s \to \pi^+K^-\)
\(~29k\ B^0 \to \pi^+\pi^-\)
\(~37k\ B^0_s \to K^+K^-\)
Event selection

- Both analyses are based on the full Run1 statistics
  - 1 fb-1 @ 7 TeV + 2 fb-1 @ 8 TeV
- Event selection is based on two main ingredients
  - Particle identification
    - Separate the final states and reduce amount of cross contamination from other $H_0 \rightarrow h^+h^-$ modes
      - Calibrated using $D^{*+} \rightarrow D^0(K^+\pi^+)$, $\Lambda \rightarrow p\pi^-$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - MVA algorithm based on BDT to reduce combinatorial background

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Final-state detection asymmetry

\[ A_F = A_{\text{PID}} + A_D \]

- \( A_{\text{PID}} \) determined using \( D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+ \), \( \Lambda \rightarrow p\pi^- \) and \( \Lambda_c^+ \rightarrow pK^-\pi^+ \)

- \( A_D \) for K
  - using raw asymmetries of Cabibbo-Favoured charm decays \( D^+ \rightarrow K^-\pi^+\pi^+ \) and \( D^+ \rightarrow K^0\pi^+ \) [JHEP 07 (2014) 041]

- \( A_D \) for \( \pi \)
  - from partial reconstruction of \( D^{*+} \rightarrow D^0(K^-\pi^+\pi^-\pi^+)\pi^+ \) decays [PLB 713 (2012)]

- \( A_D \) for p
  - determined from simulation
  - generous systematic assigned due to the assumptions made regarding p/p interaction cross-section
Results

\[ A_{CP}^{B^0} = -0.084 \pm 0.004 \pm 0.003 \]
\[ A_{CP}^{B^0_s} = 0.213 \pm 0.015 \pm 0.007 \]

• Main syst.:
  – \( B^0 \): Det. asymmetry
  – \( B^0_s \): mass model

SM test assuming U-spin validity [PLB621(2005)126]

\[
\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B^0_s}} + \frac{B(\overline{B}^0 \to \pi^+K^-)\tau_d}{B(\overline{B}^0 \to \overline{K}^+\pi^-)\tau_s} = -0.11 \pm 0.04 \pm 0.03
\]
from \( A_{CP} \)

• Thanks to the time-dependent analysis the production asymmetries are automatically subtracted
  – \( A_p(B^0) = (0.19 \pm 0.60)\% \)
  – \( A_p(B^0_s) = (2.4 \pm 2.1)\% \)

Compatible with expectation from Phys. Lett. B 774 (2017) 139
Results

LHCb-PAPER-2018-025 / PRELIMINARY

\[ A_{\text{CP}}^{pK} = -0.020 \pm 0.013 \pm 0.019, \]
\[ A_{\text{CP}}^{p\pi} = -0.035 \pm 0.017 \pm 0.020, \]

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>( A_{\text{CP}}^{pK} [%] )</th>
<th>( A_{\text{CP}}^{p\pi} [%] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon or pion detection asymmetry</td>
<td>0.23</td>
<td>0.11</td>
</tr>
<tr>
<td>Proton detection asymmetry</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>PID asymmetry</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>( A_0^b ) production asymmetry</td>
<td>1.40</td>
<td>1.40</td>
</tr>
<tr>
<td>Trigger asymmetry</td>
<td>0.53</td>
<td>0.55</td>
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<tr>
<td>Signal model</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Background model</td>
<td>0.23</td>
<td>0.47</td>
</tr>
<tr>
<td>PID efficiencies</td>
<td>0.57</td>
<td>0.74</td>
</tr>
<tr>
<td>Total</td>
<td>1.91</td>
<td>2.00</td>
</tr>
</tbody>
</table>

\[ \Delta A_{\text{CP}} \equiv A_{\text{CP}}^{pK} - A_{\text{CP}}^{p\pi} \]
\[ 0.014 \pm 0.021 \pm 0.013 \]

Error reduced by more than x4 with respect to CDF 😊

No evidence for CPV 😞

- \( A_p \) is determined weighting the result in Phys. Lett. B 774 (2017) 139 for signal kinematics
Flavour tagging

- In this analysis tagging is used on a per-event basis
  - **Opposite Side (OS)** taggers
  - **Same Side (SS)** taggers
    - SSπ and SSP for B^0
    - SSK for B_s^0

- Calibration of mistag fraction \( \omega \):
  - Use time-dependent asymmetry of \( B^0 \to K^+\pi^- \) to calibrate OS, SS\( \pi \) and SSP
  - Use time-dependent asymmetry of \( B_s^0 \to D_s^-\pi^+ \) to calibrate SSK
Decay time resolution

- Calibration is performed measuring simultaneously the time-dependent asymmetries of $B^0 \rightarrow D^- \pi^+$ and $B_s^0 \rightarrow D_s^- \pi^+$ decays
  - Dilution from flavour tagging calibrated thanks to $B^0 \rightarrow D^- \pi^+$
  - Additional dilution in the $B_s^0 \rightarrow D_s^- \pi^+$ decay allows to calibrate decay-time resolution
  - Portability from $B \rightarrow D_h$ to $B \rightarrow h_h$ is studied on simulation

\[ D = \exp(-\sigma_t \Delta m^2/2) \]
Decay-time acceptance

- Reconstruction efficiency as a function of decay-time is determined using $B^0 \rightarrow K^+\pi^-$ decays
  
  - Untagged decay rate of $B^0$ as a function of time is a pure exponential
  
  - For the other decay modes, simulation is used to study the differences

[Graphs showing efficiency as a function of time for various decay modes]
Results

\[ C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01 \]
\[ S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01 \]
\[ \rho(C_{\pi\pi}, S_{\pi\pi}) = 0.448 \]

* Most precise from a single experiment
  – x2 better precision than previous LHCb
* Main syst.: cross-feed and 3-body model

Fixed parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m_d )</td>
<td>( 0.5065 \pm 0.0019 \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>( \Gamma_d )</td>
<td>( 0.6579 \pm 0.0017 \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>( \Delta \Gamma_d )</td>
<td>0</td>
</tr>
<tr>
<td>( \Delta m_s )</td>
<td>( 17.757 \pm 0.021 \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>( \Gamma_s )</td>
<td>( 0.6654 \pm 0.0022 \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>( \Delta \Gamma_s )</td>
<td>0.083 \pm 0.007 \text{ ps}^{-1}</td>
</tr>
<tr>
<td>( \rho(\Gamma_s, \Delta \Gamma_s) )</td>
<td>( -0.292 )</td>
</tr>
</tbody>
</table>
**Results**

\[
C_{K+K^-} = 0.20 \pm 0.06 \pm 0.02 \\
S_{K+K^-} = 0.18 \pm 0.06 \pm 0.02 \\
A_{K+K^-}^{\Delta \Gamma} = -0.79 \pm 0.07 \pm 0.10
\]

- Main syst.: decay-time resolution, decay time acceptance and input parameters
- First measurement of \(A_{KK}^{\Delta \Gamma}\)
- Strong evidence of CPV (~4\(\sigma\)) in \(B_s^0 \rightarrow K^+K^-\)

**Fixed parameters**

<table>
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<tbody>
<tr>
<td>(\Delta m_d)</td>
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</tr>
<tr>
<td>(\Gamma_d)</td>
<td>0.6579 ± 0.0017 ps(^{-1})</td>
</tr>
<tr>
<td>(\Delta \Gamma_d)</td>
<td>0</td>
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<tr>
<td>(\Delta m_s)</td>
<td>17.757 ± 0.021 ps(^{-1})</td>
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<tr>
<td>(\Gamma_s)</td>
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</tr>
<tr>
<td>(\Delta \Gamma_s)</td>
<td>0.083 ± 0.007 ps(^{-1})</td>
</tr>
<tr>
<td>(\rho(\Gamma_s, \Delta \Gamma_s))</td>
<td>-0.292</td>
</tr>
</tbody>
</table>

[arXiv:1805.06759]
Conclusions

• The latest measurements of CPV in b-hadron decays to charmless charged two-body final states at LHCb have been presented
  – All the analyses are based on the full Run1 sample corresponding to 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

• Significant improvement with respect to previous measurements for all the presented quantities
  – Best measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ from a single experiment
  – Strong evidence of CPV in $B_s^0 \rightarrow K^+K^-$ decay at 4$\sigma$
  – $A_{CP}$ in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ have precisions 4 times better than previous measurement from CDF
  – No evidence of deviations from the SM

• Already x3 statistics is available from Run2
Backup
The LHCb detector
The LHCb detector

- **Vertex Locator (VELO)**
- **Silicon micro-strips**
- **RICH**
  - Three different radiators in order to cover a wide momentum range
- **Dipole magnet**
  - 4 Tm
- **Tracking stations**
  - Silicon micro-strips and straw-tubes
- **HCAL, ECAL and Preshower/SPD**
- **Muon detector**
How to exploit $H_b \rightarrow h^+h'^-$ decays

- CP asymmetries of $B^0 \rightarrow \pi^+\pi^-$
  - fundamental input to the isospin analysis to determine the CKM angle $\alpha$
- First proposal to include also $B_s \rightarrow K^+K^-$ decays dates back to 1999
  - exploiting U-spin symmetry to constraint QCD uncertainties and determine $\gamma$ and $-2\beta_s$
- $A_{CP}$ of $B^0 \rightarrow K^+\pi^-$ and $B_s \rightarrow \pi^+K^-$ provide a test of the SM assuming U-spin symmetry

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s}} + \frac{\mathcal{B}(B_s \rightarrow \pi^+K^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0$$
How to exploit $H_b \rightarrow h^+h'^-$ decays

- More recent studies aimed to reduce the impact of the uncertainty due to $U$-spin breaking
  - Combined analysis of $B^{0,\pm} \rightarrow \pi^{0,\pm}\pi^{0,\pm}$ and $B_s \rightarrow K^+K^-$

- Combining CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ with information from semileptonic $B^0 \rightarrow \pi\ell\nu$ and $B_s \rightarrow K\ell\nu$ allow to reduce the usage of $U$-spin symmetry

# Systematic uncertainties

**arXiv:1805.06759**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$C_{\pi^+\pi^-}$</th>
<th>$S_{\pi^+\pi^-}$</th>
<th>$C_{K^+K^-}$</th>
<th>$S_{K^+K^-}$</th>
<th>$A_{K^+K^-}^{\Delta\Gamma}$</th>
<th>$A_{CP}^{B^0}$</th>
<th>$A_{CP}^{B^0_s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-dependent efficiency</td>
<td>0.0011</td>
<td>0.0004</td>
<td>0.0020</td>
<td>0.0017</td>
<td>0.0778</td>
<td>0.0004</td>
<td>0.0002</td>
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<tr>
<td>Time-resolution calibration</td>
<td>0.0014</td>
<td>0.0013</td>
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<td>0.0119</td>
<td>0.0951</td>
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<tr>
<td>Time-resolution model</td>
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<td>0.0005</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0003</td>
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<td>negligible</td>
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<tr>
<td>Input parameters</td>
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<td>0.0024</td>
<td>0.0092</td>
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<tr>
<td>OS-tagging calibration</td>
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<td>0.0021</td>
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<td>—</td>
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<td>Cross-feed time model</td>
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<td>0.0059</td>
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<td>0.0024</td>
<td>0.0003</td>
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<tr>
<td>Three-body bkg.</td>
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<td>0.0056</td>
<td>0.0044</td>
<td>0.0043</td>
<td>0.0304</td>
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<tr>
<td>Comb.-bkg. time model</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0004</td>
<td>0.0002</td>
<td>0.0019</td>
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<tr>
<td>Signal mass model (resol.)</td>
<td>0.0027</td>
<td>0.0025</td>
<td>0.0015</td>
<td>0.0015</td>
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<td>Signal mass model (tails)</td>
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<td>0.0002</td>
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<td>0.0001</td>
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<td>PID asymmetry</td>
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<td>—</td>
<td>0.0014</td>
<td>0.0014</td>
<td>0.0014</td>
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<td><strong>Total</strong></td>
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<td><strong>0.0095</strong></td>
<td><strong>0.0165</strong></td>
<td><strong>0.0191</strong></td>
<td><strong>0.0966</strong></td>
<td><strong>0.0030</strong></td>
<td><strong>0.0066</strong></td>
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